Slope Stability Evaluations Using Digital Terrain Models

Land Management Report NUMBER 74

ISSN 0702-9861

FEBRUARY 1992

BC

FISH/FORESTRY INTERACTION PROGRAM

This study was undertaken as part of the Fish/Forestry Interaction Program (FFIP), a multidisciplinary research study initiated in 1981. The program was started following a series of major winter storms in 1978 that triggered landslides over much of the Queen Charlotte Islands forest land base. Originating on steep slopes, many slides deposited tonnes of debris in streams and on valley flats. The events raised private and public concerns over logging practices on the Islands and prompted the establishment of the 5-year program. Overall objectives of FFIP were:

- to study the extent and severity of mass wasting and to assess its impacts on fish habitat and forest sites;
- to investigate the feasibility of rehabilitating stream and forest sites damaged by landslides;
- to assess alternative silvicultural treatments for maintaining and improving slope stability; and
- to investigate the feasibility and success of using alternative logging methods, including skylines and helicopters, and by logging planning to reduce logging-related failures.

The program is jointly funded by direct appropriations from the Canada Department of Fisheries and Oceans, the B.C. Ministry of Forests (Forest Science Research Branch), and the B.C. Ministry of Environment (Fisheries Branch). Participating agencies include Forestry Canada (Pacific Forestry Centre), and the Forest Engineering Research Institute of Canada (FERIC), Vancouver, B.C.

Program results are published through the B.C. Ministry of Forests, Land Management Report series, as well as in papers presented at symposiums, conferences, and through technical journals.

For information about the program contact Ministry of Forests, Forest Science Research Branch, 31 Bastion Square, Victoria, B.C. V8W 3E7.

92-05155/

Slope Stability Evaluations Using Digital Terrain Models

by
K.O. Niemann[1] and D.E. Howes[2]

[1] Department of Geography
University of Victoria
P.O. Box 3050
Victoria, B.C.
V8W 3P5

[2] B.C. Ministry of Environment
Environmental Emergency Services Branch
737 Courtney Street
Victoria, B.C.
V8V 1X5

February 1992

Canadian Cataloguing in Publication Data

Niemann, Knut Olaf, 1953-
Slope stability evaluations using digital terrain models

(Land management report, ISSN 0702-9861 ; no. 74)

Includes bibliographical references: p.
ISBN 0-7718-9079-6

1. Logging - Environmental aspects - British Columbia - Fraser-Cheam - Computer simulation. 2. Mass-wasting - British Columbia - Fraser-Cheam - Computer simulation. 3. Slopes (Soil mechanics) - British Columbia - Fraser-Cheam - Computer simulation. 4. Fraser-Cheam (B.C.) - Relief models. I. Howes, D. E. (Don Edwin), 1948- II. British Columbia. Ministry of Forests. III. Title. IV. Series.

SD424.N53 1992 551.3'070113 C91-092257-8

© 1992 Province of British Columbia
Published by the
Forest Science Research Branch
Ministry of Forests
31 Bastion Square
Victoria, B.C. V8W 3E7

Copies of this and other Ministry of Forests titles are available from Crown Publications Inc., 546 Yates Street, Victoria, B.C. V8W 1K8.

TABLE OF CONTENTS

1 INTRODUCTION 1

2 DEFINITION OF TERMS 2

3 STUDY AREA 3

3.1 Physical Setting 3

4 MULTIFACTOR SLOPE STABILITY STUDY 4

5 METHOD 5

6 RESULTS 13

6.1 Landscape Morphological Modelling 13
6.2 Morphological Classification 13
6.3 Clearcut Cluster Hazard Ratings 16

7 CONCLUSIONS 19

APPENDIX 1. FORTRAN Programme Listings 20

REFERENCES 28

TABLES

1. Multifactor approach classification strategy (Howes, 1987) 4
2. Summary of cluster descriptive statistics (standard deviation in brackets) 14
3. Morphological classification summary 14
4. Clearcut classification summary 17

FIGURES

1. Study area location 3
2. Conventional multifactor slope stability for the Norrish-Cascade watersheds. See Table 1 for explanation of categories 6
3. Grey tone representation of the digital elevation model 6
4. Notation convention for 3 x 3 pixel kernel 7
5. Schematic representation of flow path model 8
6. Grey tone representations of the spatial models: a) slope gradient; b) across slope curvature; c) downslope curvature; and d) flow path 9
7. Example of plot of CCC vs number of clusters. Groups were clustered (Figure 8). These are clustered simultaneously because together they represent the shape of the landform 11
8. Schematic of the clustering process 12
9. Morphological hazard classification 15
10. Clearcut hazard classification 18

1 INTRODUCTION

Slope stability analysis is an essential task for managers of natural resources in steep land or in areas subjected to shallow mass movement. A number of different strategies for predicting areas of slope instability, or modelling their likelihood, have been developed. They range from simple inventories of existing mass movements to multiple factor mapping of slope, geology, soil, and other variables (Sidle *et al.* 1985). Landslide inventories have limited value because their applicability relies on the skills of the individual interpreters. The potential for extrapolating the results of the inventory into areas that have not experienced mass movements is also limited.

The most common strategy for assessing landslide hazard is that of modelling. Several different modelling strategies have been developed. They vary from the simplest, correlating a single variable such as slope gradient or a soil property with the occurrence of mass movements, to multifactor or multivariate analysis (see, for example Carrara 1983; Pack 1985; Howes 1987).

The basic assumption in the univariate models is that slope instability is dictated by a single variable or process. The more attractive multivariate modelling approach assumes that processes operating on the landscape are influenced to a greater or lesser degree by multiple factors. The disadvantage of this latter approach is its very large data, and thus processing, requirements. This increases their cost significantly over the single variate approaches. One of the challenges to earth science is to develop and refine slope stability analyses that take advantage of multivariate modelling techniques, while minimizing data requirements.

Several factors affect slope stability (Sharpe 1938; Sidle 1985). Slope gradient and slope shape, and the influence of shape on the distribution of soil moisture, are important factors influencing shallow mass movements. Slope gradient has been closely related to shallow mass movement processes (Swanston 1974; Sidle *et al.* 1985). For example, most slopes covered by unconsolidated materials, in general over 35 degrees, are subject to shallow mass movements (Sidle *et al.* 1985).

The shape of the slope can strongly influence the distribution of soil water: concave slopes concentrate soil water; convexities disperse moisture. This accounts for the frequent association of shallow mass movements with slope depressions and gullies, although this type of landslide can occur on straight slopes in profile (Sidle *et al.* 1985).

A common theme in multifactor slope stability studies has been to incorporate landscape morphology (slope gradient and curvature) and soil moisture distribution and movement information. Traditionally, three sources were used to obtain this type of information: aerial photographs, topographic maps, and field surveys (Rib and Liang 1978). Extensive use of these techniques allows the investigator to study the landscape within a three-dimensional perspective. The use of these survey techniques facilitates the integration of landscape shape elements with vegetative, geomorphological, and pedological factors in an appraisal of mass movement hazards.

The disadvantage of this type of technique, as mentioned above, is that of high cost. A need therefore exists for inexpensive, systematically collected data related to earth surface morphology (slope gradient, shape, soil moisture movement), to be used in multifactor slope stability studies. Digital Terrain Models (DTM) have the potential to satisfy this need. They are systematic in their approach, useful for describing the morphometric properties of the terrain, and inexpensive to develop.

This paper investigates the potential to use these models for slope stability mapping. First, a short review of digital elevation models is presented, and then the use of empirical modelling within the context of this project is explored. Finally, the rationale for the stability classifications developed in this paper are addressed.

2 DEFINITION OF TERMS

The term "digital terrain model" or "digital elevation model" (DTM or DEM) refers to a numerical representation of the earth's surface (Yoeli 1984). Both the DTM and DEM are representations of surface form. According to Burrough (1986), the difference between the two terms lies in the fact that DTM's may also include other terrain - related information such as water courses. Most commonly, elevation is represented through a regularly spaced matrix of elevations, or an irregular network of elevation points referred to as a Triangular Irregular Network (TIN), although other techniques may also be employed. Models are generated either from aerial photographs through the use of traditional photogrammetric techniques (Wolf 1983), or from existing topographic maps that have been converted into a digital format.

Both of these data organizational strategies have advantages and disadvantages. The major advantage of the TIN is that areas of high topographic variation may be sampled with a higher density of points than an area where relief is uniform. The disadvantage of this sampling strategy is that the observed topographic variation may have a different significance for the photogrammetrist than for the earth scientist. The result of these different interpretations is that relatively subtle differences in relief may not be recorded in a TIN, and such differences could be of importance to the soil scientist or geomorphologist.

In the case of the regularly spaced elevation matrix, the sampling rate is consistent across the area in question, irrespective of the nature of the topography. The result of this sampling strategy is that the entire geographic area is defined by a uniform distribution of points. The disadvantage of this approach is that sudden breaks in the terrain slope may not be captured by the sampling process.

A third, hybrid alternative combines these two strategies. As a method of data collection, it ensures that an area will be sampled on a regular basis, and that a sample of all of the breaks in slope will also be collected. These two samples are subsequently integrated to form a single, composite data set.

The evaluation of the physical properties of the earth's surface was termed "geomorphometry" by Evans (1972). He defined a variety "landscape morphological models" in his paper, which can be used individually or in combination, to describe the geomorphologic or pedologic characteristics of a landscape. These models are mathematically derived in the case of this study from a DEM, and usually are based on the first (slope gradient) and second (curvature) derivatives of elevation. In addition, a number of other geomorphometric, or landscape, models (for example slope aspect, slope position, and relief) can be developed. These landscape morphological variables are described in detail later in the paper.

The methods used to model slope stability, in this study, were empirical rather than physical. In most natural situations the knowledge of all boundary conditions is incomplete and therefore a full understanding of the natural processes is not possible. Broad assumptions must be made about the distribution of materials or conditions, and the use of these assumptions dictates that statistically based, empirical models be applied. Empirical modelling techniques require the use of interval-scaled, normally distributed data. This precludes the incorporation of most mapped sources, which are, for the most part, nominal or ordinal. The data contained in the DEM's are, however, interval scaled.

Finally, the term "shallow mass movements" in unconsolidated sediments refers to the moderate to rapid downslope movement of materials by sliding or flowing, commonly over impermeable substrate. These forms include debris slides, flows, avalanches, and torrents (cf. Sharpe 1938; Swanston 1974; and Varnes 1978). "Shallow mass movement", in the context of this paper, is used interchangeably with the term "landslide".

3 STUDY AREA

The study area chosen for this project is located 65 km east of Vancouver, B.C. and includes the Norrish and Cascade watersheds (Figure 1). The existence of a multifactor slope stability analysis study and an extensive data base on mass movements of the area (Howes 1987) was the basis for selection.

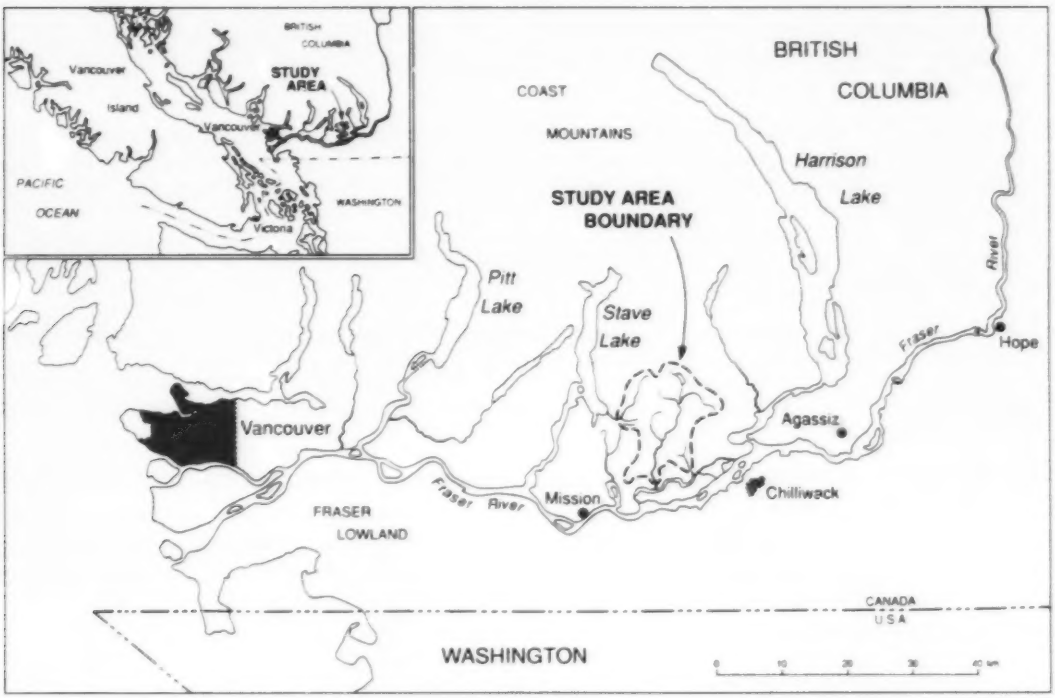


FIGURE 1. Study area location.

3.1 Physical Setting

The Norrish and Cascade watersheds are underlain by granitic rocks of the Coast Plutonic Rocks (Roddick 1965). Both valleys have been subject to multiple glaciations during the Pleistocene Epoch and were completely inundated during the most recent, Fraser Glaciation (Armstrong *et al.* 1965).

Most of the surficial deposits and landforms in the area are the result of this latter glaciation and subsequent post-glacial reworking by fluvial and colluvial processes. The upper slopes in the valleys are overlain by a thin, discontinuous mantle of glacial till or colluvium, with frequent rock outcrops. Lower valley sides are characterized by thick, continuous till and colluvial deposits, with some small inclusions of glaciofluvial materials. Valley bottoms are covered by glaciofluvial and holocene fluvial materials. These sediments have been incised to produce a series of terrace levels.

Mass movement processes, such as rockfalls, debris slides, flows and torrents, and rotational slumps, are active on the valley side slopes. The area is characterized by cool wet winters and dry warm summers. Winter storms are often intense and are considered to be one of the important triggering mechanisms of the shallow mass movements.

4 MULTIFACTOR SLOPE STABILITY STUDY

A slope stability study was conducted in the Norrish and Cascade watersheds between 1984 and 1986 by the B.C. Ministry of Environment (Howes 1987). The purpose of the study was to develop a multifactor terrain evaluation methodology for predicting terrain susceptible to post-logging landslide activity, and to apply the method to resource management of the watersheds.

The method developed consisted of six steps (for specific details see Howes 1987):

1. mapping, on aerial photographs, the surficial geology according to the Terrain Classification System to define homogeneous areas of material, texture, surface expression and process. Additional data, such as slope, aspect, drainage, and bedrock type for each terrain unit (polygon), were also obtained from topographic, geologic sources;
2. collecting, mapping and analyzing the landslide site data to identify factors contributing to clearcut landslides. Factors identified after analysis included type of surficial materials, "critical" slope angles for different material types, slope configuration, drainage, depth of material, and presence or absence of gully erosion;
3. defining a set of classes based on the terrain factors, such that each polygon can be assigned to only one class (Table 1);
4. calculating for each new terrain class several stability statistics (based on data obtained from landslide and terrain inventory programmes) related to both natural and clearcut failures;
5. grouping the terrain classes into four stability classes based on the ratio of the number of clearcut-induced slides to the number of clearcut hectares; and
6. producing a computer-generated map displaying the polygons labelled according to the stability class and other criteria.

The slope stability map for the Norrish and Cascade watersheds, produced by this method, is presented in Figure 2. It can be compared with the DEM-generated maps, developed through the methodology described in this report.

Table 1. Multifactor approach classification strategy (Howes 1987)

Material	Slope (%)	Shape	Process	Drainage	Rating
colluvium	>36	uniform	gullied	rapid	HIGH
till; till/coll.	>33	uniform	gullied	rapid-mod.	
unconsolidated scarp	>33	uniform		rapid-mod.	
colluvium	>36	uniform		rapid	MODERATE
till; till/coll.	>33	uniform		rapid-mod.	
till; till/coll.	>26-<33	uniform	gullied	rapid-mod.	
colluvium	>29-<36	uniform	gullied	rapid	
fluvial	>20-<33	uniform		rapid-mod.	LOW
till; till/coll.	>26-<33	uniform		rapid-mod.	
colluvium	>29-<36	uniform		rapid	
rock/coll.	>30	uniform		rapid	
till	>26	uniform		mod.-rapid	VERY LOW
fluvial	>20	uniform	active flooding		
colluvial	>36	uniform	active fans		
fluvial	>20	uniform		rapid-mod.	
till or coll.	>20	uniform		rapid-mod.	
till or coll.	variable	irregular		rapid	
fluv. over till	<33	uniform		rapid-mod.	

5 METHOD

The method used in this study involved five steps:

1. Digital terrain modelling;
2. Landscape morphological modelling;
3. Statistical modelling;
4. Classification of clusters for slope stability analysis; and
5. Qualitative comparison of the resulting stability classification to the traditional multifactor stability results of the Norrish and Cascade watersheds.

Step 1. Digital Elevation Modelling

The DEM data set developed for the Norrish-Cascade study area was derived through the regular sampling strategy. The grid was generated by analytical photogrammetric techniques. It had a resolution of 50 m, with a minimum horizontal accuracy of +/-10 m and a minimum vertical accuracy of +/-5 m. This was done rather than integrating the breaklines with the regular grid because it was felt that with the 50 m grid cell resolution the breaklines would be accounted for. A grey tone representation of this DEM is displayed in Figure 3.

Step 2. Landscape Morphological Modelling

The DEM elevation grid can be manipulated through a variety of analytical techniques to produce landscape morphological models. For this study we developed five models to describe different morphological properties. The first two, and most common models, were based on the determination of the slope gradient (or the first spatial derivative of elevation), and on the orientation (or aspect) of the slope facet with the maximum gradient. Two additional morphological models derived included the second derivative of elevation, or curvature, which was calculated in the upslope and across slope directions.

In this study, we used the method described by Zevenbergen and Thorne (1987) to derive the spatial derivatives of the DEM. Their algorithm relies on the use of a third order Lagrange polynomial to derive the derivatives.

$$Z = AX^2Y^2 + BX^2Y + CXY^2 + DX^2 + EY^2 + FXY + GX + HY + I$$

where: Z = elevation of the grid cell at position X,Y
A -I = coefficients of the polynomial
X,Y = grid cell location

The coefficients A through I can be evaluated through the relationships:

$$A = [(Z_1+Z_3+Z_7+Z_9)/4 - (Z_2+Z_4+Z_6+Z_8)/2 + Z_5] / GS^4$$

$$B = [(Z_1+Z_3-Z_7-Z_9)/4 - (Z_2-Z_8)/2] / GS^3$$

$$C = [(-Z_1+Z_3-Z_7+Z_9)/4 - (Z_4-Z_6)/2] / GS^3$$

$$D = [(Z_4+Z_6)/2 - Z_5] / GS^2$$

$$E = [(Z_2+Z_8)/2 - Z_5] / GS^2$$

$$F = (-Z_1+Z_3+Z_7-Z_9) / (4*GS^2)$$

$$G = (-Z_4+Z_6) / 2*GS$$

$$H = (Z_2-Z_8) / 2*GS$$

$$I = Z_5$$

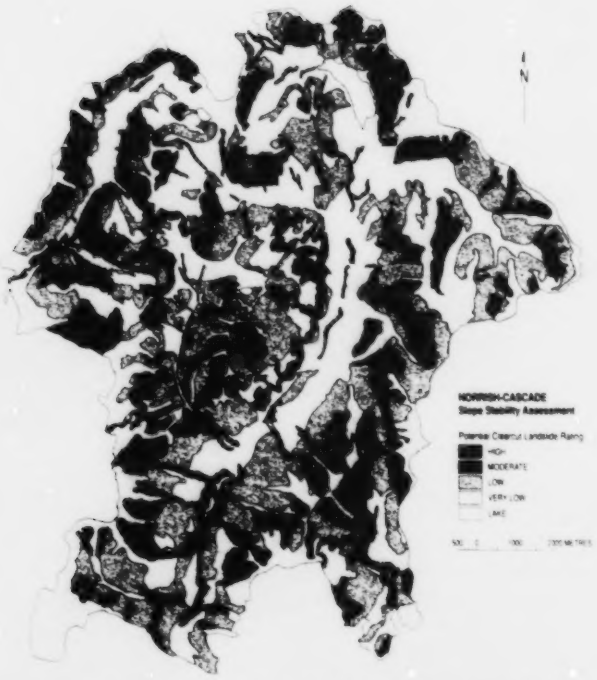


FIGURE 2. Conventional multifactor slope stability for the Norrish-Cascade watersheds. See Table 1 for explanation of categories.

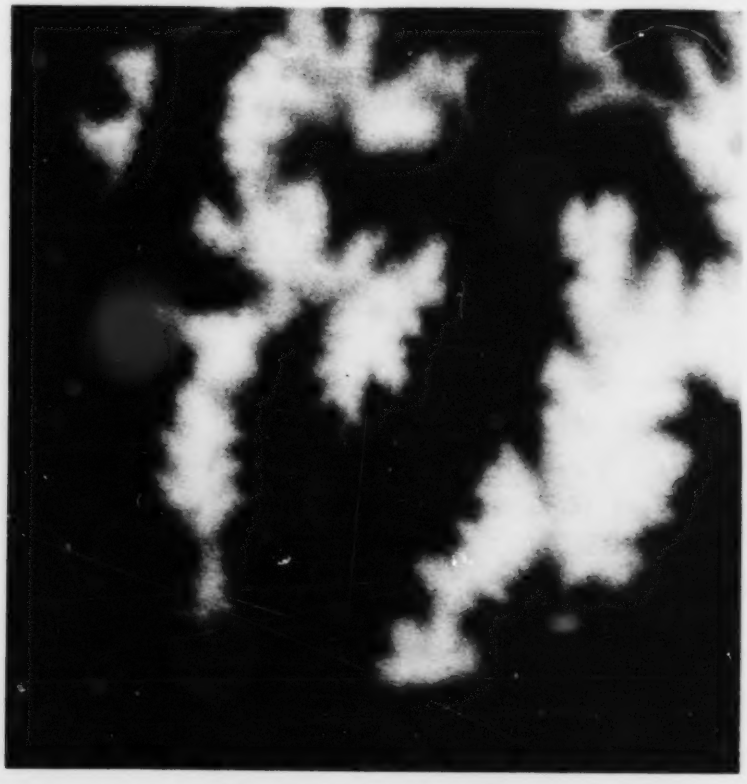


FIGURE 3. Grey tone representation of the digital elevation model.

where: GS = the grid cell size
Z_1 = the elevation at grid cell 1 of the 3 x 3 submatrix. The numbering scheme for the 3 x 3 matrix is given in Figure 4.

The spatial derivatives were derived from the following computations:

Slope gradient = $-(G^2 + H^2)^{0.5}$

Direction of maximum gradient= ARCTAN(-H / -G)

$$\text{Downslope curvature} = \frac{-2(DG^2 + EH^2 + FGH) / (G^2 + H^2)}{(1 + G^2 + H^2)^{1.5}}$$

$$\text{Across slope curvature} = \frac{-2(DH^2 + EG^2 - FGH)}{(G^2 + H^2)^{1.5}}$$

Third order polynomials provide a higher degree of accuracy than do other techniques using lower order equations (see for example, Heerdegen and Beran 1982).

The third order equation is an exact fit of a surface passing through the 3 x 3 grid cell elevation submatrix used to derive the spatial derivatives. In contrast, lower order polynomial equations produce a surface fit that is not exact, and thus the derivatives calculated are only approximated. The use of a second order polynomial, therefore, will introduce computational inaccuracies that compound the measurement errors introduced into the production of the DEM. A FORTRAN 77 listing of the programme used in this study is included in Appendix 1.

The above morphological models may be referred to as local models, as they derive information related to a restricted area surrounding the 3 x 3 grid cell. Another model was introduced to generate information on a regional basis. The rationale for this model was that the area upslope of a particular point contributed to the total amount of moisture flowing through that point. The method used in this study to

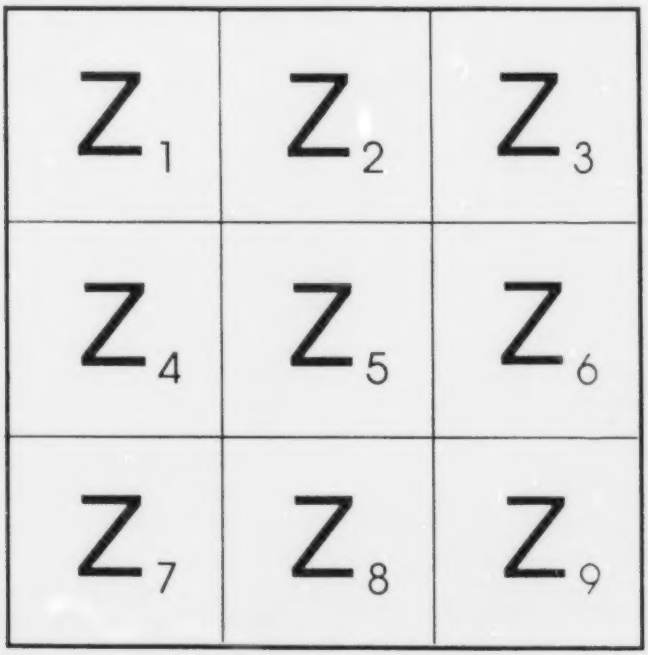


FIGURE 4. Notation convention for 3 x 3 pixel kernel.

calculate the drainage area was, in part, based on that suggested by O'Callaghan and Mark (1984). The algorithm traces paths of maximum slope during a recursive descent from a grid cell down to a closed depression, or the edge of the elevation matrix (see Figure 5). During the trace of this path, the total upslope area contributing flow to a grid cell along the flow path is determined. The result of the area calculation is written to an answer matrix corresponding in size to the original DEM. The FORTRAN 77 listing for this programme can be found in Appendix 1. Grey tone representations for all of the individual data sets generated from the modelling procedures are presented in Figure 6.

Elevation Matrix

140	135	130	125	120	130	137	140	146	146
130	125	110	100	100	110	125	125	125	130
105	100	90	80	85	95	100	100	105	110
85	75	70	65	67	72	75	80	87	90
60	65	55	51	53	55	57	69	62	65
40	43	40	38	39	43	50	57	60	53

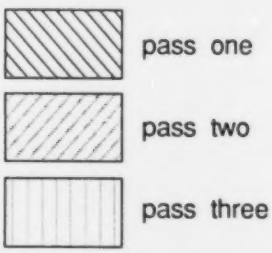


FIGURE 5. Schematic representation of flow path model.

Step 3. Statistical Modelling

The basic assumption followed in this study is that a landform or landscape may be divided into a number of morphological clusters, or groupings, which, when considered jointly, describe the entire landscape. Given the intimate relationship between form and process in the earth sciences, these morphological groupings can be correlated with the process operating on the landscape. The statistical modelling we used in this study is concerned with differentiating the existing morphological facets of the Norrish and Cascade watersheds. Once these groupings and their descriptive statistics have been identified, their association with the processes related to slope stability can be identified.

The morphological data base composed of slope gradient, downslope and across slope curvatures, and the upslope drainage area was sampled systematically, using a sampling interval of 250 m. This resulted in a data set of 4188 points which could be used for a statistical evaluation. This sample set was subjected to an unsupervised cluster analysis. The rationale for using a cluster analysis was that there was no *a priori* knowledge of the relationship of the morphological coverages and the terrain found in the Norrish and Cascade watersheds.

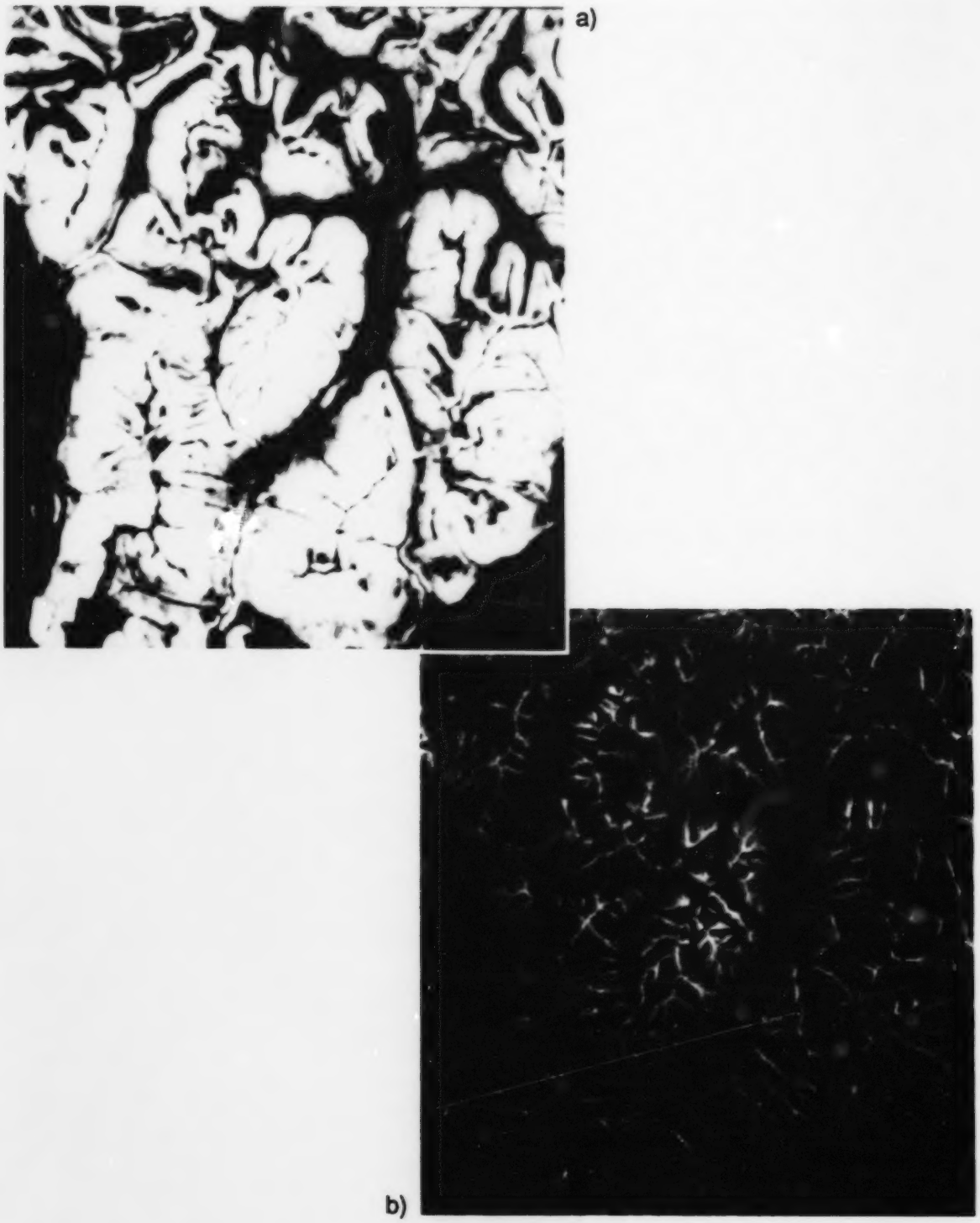
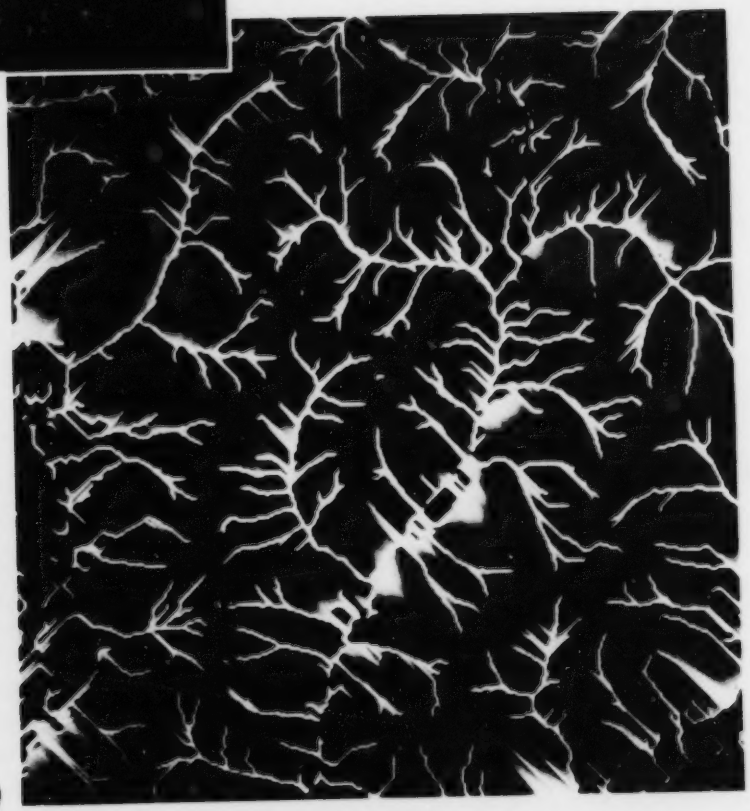


FIGURE 6. Grey tone representations of the spatial models: a) slope gradient; b) across slope curvature; c) downslope curvature; and d) flow path.

c)



d)

FIGURE 6. (continued).

Cluster analysis determines the number of clusters present in the data set. This problem has been addressed by Sarle (1983) who suggested the use of a statistic describing the optimization criterion for disjoint clusters of observations, referred to as the Cubic Clustering Criterion (CCC). By performing a series of cluster analyses, progressively increasing the number of candidate clusters, we can produce a set of CCC values. When the CCC values are plotted against the corresponding number of clusters, an interpretation of the appropriate number of clusters represented by the data set can be made. A major break in the slope following a steep upward rise in the line tracing the plotted points suggests a possible candidate number of clusters.

Data distributions with differing forms result in differing CCC curves. Spherically distributed data sets yield a distinctive peak followed by a sharp rise in the CCC values. Elliptical cluster shapes result in a rapid rise in the CCC value with an increasing number of clusters, followed by a break in the slope of the curve, a gentle increase in the CCC values rising to a peak, and a subsequent decrease in the CCC values.

These plots must be interpreted with care, as multiple peaks may represent a possible subdivision of the data sets into smaller, and sometimes meaningless, subclusters. Sarle (1983) notes that the magnitude of the CCC values indicates the degree of separation of the clusters. Strongly positive CCC values show a high degree of separation; negative values show a substantial degree of overlap between the clusters. For example, Figure 7 illustrates the CCC values plotted against the number of clusters for the slope variable. The CCC values are low, indicating that a substantial degree of overlap exists between the clusters. A similar trend was observed for the drainage and curvature variables.

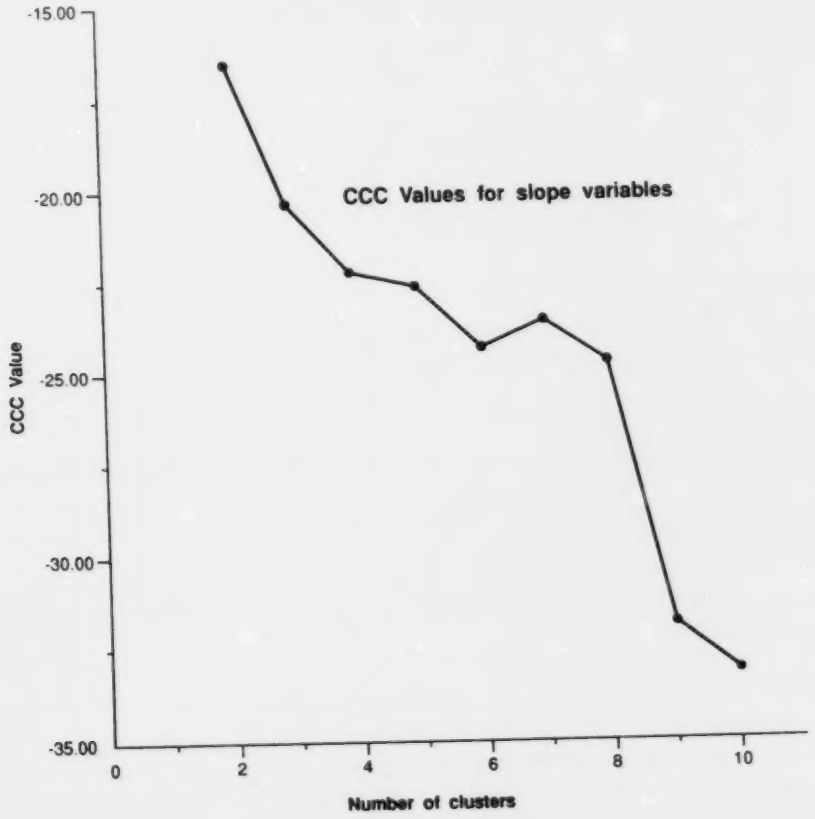


FIGURE 7. Example of plot of CCC vs number of clusters. Groups were clustered (Figure 8). These were clustered simultaneously because together they represent the shape of the landform.

A stratified procedure was adopted to cluster the data set sampled from the morphological data base. This procedure independently clustered the morphological variables using a k- means cluster analysis (SAS 1987). Slope gradient was the first variable to be clustered. The second was upslope drainage area. The clustering with the drainage variable was carried out on the individual groups created through the original clustering based on slope gradient. Finally, both the curvature values for the sample points occurring within each of the resulting groups were clustered (Figure 8). These were clustered simultaneously because together they represent the shape of the landform.

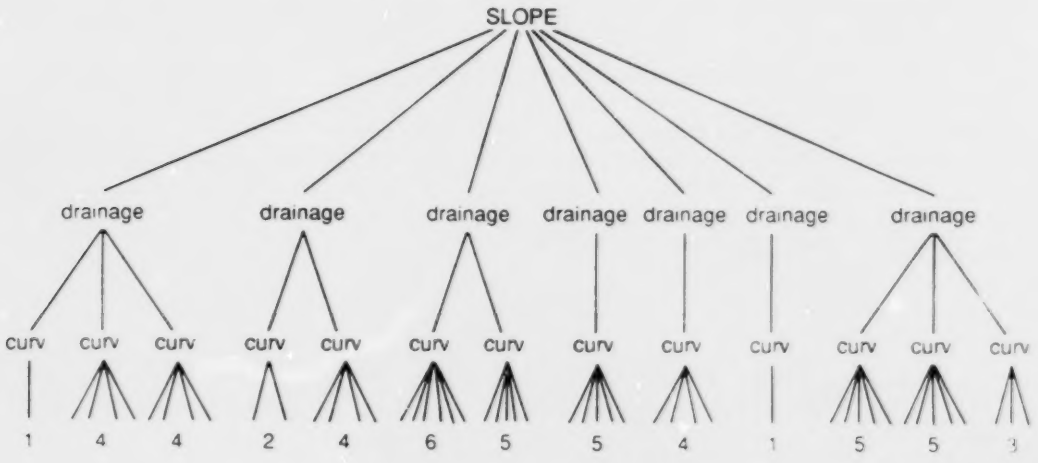


FIGURE 8. Schematic of the clustering process.

Step 4. Classification of Clusters

Two classification schemes for the clusters were developed to demonstrate aspects for slope stability analysis. These are referred to as the morphological and clearcut stability classifications.

Morphological Classification

The morphological classification scheme is based on the assumption that an *a priori* knowledge exists of the factors controlling the processes operating in the area. Each cluster was assigned a slope stability rating, which was initially based on slope gradient. Clusters with progressively higher slope gradient values were ranked as having successively greater failure hazards. This ranking was then subdivided according to slope position and then to the surface morphology (that is, convexity or concavity). The new cluster groups were subsequently assigned a relative stability class on the basis of the scheme used by Howes (1987).

Clearcut Classification

The second classification developed for this study was a clearcut hazard rating classification. This classification was generated through the analysis of the mass movement density for a landform cluster after clearcutting. Data related to mass movements in the photographs and transferred to a base study area were derived from the multifactor slope stability study in the Norrish-Cascade area (Howes 1987). The geographic location of the starting zones of each of the clearcut movements was converted into a

pixel address and the morphological data corresponding to each site was extracted. This resulted in 259 individual landslides being recorded along with their coincidence with clearcut sites. Those movements associated with other anthropogenic activities, such as road construction, were not included in this analysis.

Next, the areas that had been clearcut were interpreted from an aerial map. The map was digitized and converted to a grid corresponding to the area represented by the DEM. This grid was overlaid onto the morphological clusters, separating them into clearcut and natural morphological clusters. Density statistics for the clearcut clusters were determined by comparing the number of failure occurrences on a particular landscape cluster to the area occupied by the cluster. The class breakdown used follows Howes (1987).

Step 5. Comparison with Traditional Multifactor Approach

To evaluate the resulting map products, we compared them with the traditional map product. This evaluation was carried out in a qualitative because the traditional multifactor map was drawn on a base map using the 1927 North American Datum (NAD27), whereas the Digital Elevation Model used the NAD83 as the reference. The maps generated from the models were therefore visually compared to the original classification, and an interpretation of the relative performance of each of the models was made.

6 RESULTS

6.1 Landscape Morphological Modelling

The landscape morphological clustering procedure described above resulted in 44 groupings. The cluster descriptions (summarized in Table 2) were used to define the terrain classes for the final map; the cluster statistics were used in a linear discriminant analysis to classify the entire study area. This classification approach follows a linear combination of discriminating variables (in this case the morphological variables) in the form:

$$h_k = c_k + b_1 X_1 + b_2 X_2 \ldots + b_n X_n$$

where: h_k is the score for the class k

c_k is a constant for class 1

$b_{1...n}$ is a coefficient for discriminant variables 1 through n

$X_{1...n}$ is the data value for variables 1 through n.

This procedure is repeated the same number of times as there are number of classes. The decision to assign the appropriate point to a specific class is based on maximizing the between-group differences while minimizing the within-group variations. This classification approach is similar to the minimum distance procedure described in the remote sensing literature (see for example Jensen 1986).

6.2 Morphological Classification

This morphological classification strategy resulted in a grouping of the original 44 clusters into 7 classes, 6 stability classes, as well as a channel grouping. A summary of the seven class attributes and their stability ranking is presented in Table 3. To maintain consistency between the map derived from this strategy and that from traditional techniques, the number of classes were collapsed to 4: low, moderately low, moderate, and high. The map resulting from this classification is displayed in Figure 9.

TABLE 2. Summary of cluster descriptive statistics (standard deviation in brackets)

Class No.	Slope (%)	Drainage Area (x $10^3 m^2$)	Across-curvature	Down-curvature
1	78 (5)	.83 (1.4)	.0043 (.0025)	.0014 (.0030)
2	77 (4)	2.14 (2.2)	-.0004 (.0017)	-.0005 (.0035)
3	74 (2)	3.57 (1.3)	-.0065 (.001)	-.0006 (.001)
4	82 (6)	45.9 (13.7)	-.0054 (.002)	-.0022 (.001)
5	05 (4)	1.8 (3.5)	.0001 (.001)	.0000 (.001)
6	10 (2)	0 (0)	.0031 (.001)	.0077 (.001)
7	10 (5)	920.3 (114.6)	-.0031 (.004)	-.0008 (.001)
8	13 (5)	1506.95 (203.8)	-.0042 (.004)	-.0037 (.003)
9	09 (3)	134.8 (47.3)	-.0014 (.001)	-.0015 (.001)
10	08 (4)	494.4 (107.9)	-.0022 (.002)	-.0016 (.002)
11	06 (5)	44.5 (11.2)	-.0003 (.001)	-.0008 (.001)
12	13 (1)	28.7 (0.4)	-.0044 (.002)	-.0011 (.001)
13	8 (5)	14.3 (3.0)	-.0052 (.001)	-.0016 (.002)
14	52 (3)	57.5 (9.2)	-.0066 (.003)	-.0011 (.001)
15	52 (4)	5.8 (5.8)	-.0012 (.002)	-.0008 (.001)
16	53 (4)	1.1 (2.4)	.0025 (.002)	.0015 (.001)
17	52 (4)	2.2 (2.2)	.0001 (-.001)	-.0011 (.001)
18	51 (2)	27 (8.6)	-.0082 (0)	-.0027 (.001)
19	47 (1)	143.4 (38.3)	-.0058 (.004)	.001 (.001)
20	51 (3)	91.5 (8.2)	-.0067 (.004)	-.0015 (.001)
21	25 (4)	0.02 (0.1)	.0061 (.002)	.0027 (.002)
22	25 (5)	6.0 (8.6)	-.0001 (.001)	-.0005 (.002)
23	26 (4)	357 (63.8)	-.0047 (.003)	-.0020 (.002)
24	23 (5)	743 (83)	-.0043 (.003)	-.0010 (.001)
25	27 (7)	179 (48.3)	-.0043 (.002)	-.001 (.001)
26	21 (4)	55 (8.1)	-.0037 (.002)	-.0030 (.002)
27	23 (6)	85.5 (6.8)	-.6066 (.001)	-.0016 (.001)
28	102 (12)	.84 (1.45)	.0014 (.002)	-.0036 (.006)
29	98 (14)	1.56 (1.7)	-.0009 (.001)	-.0010 (.001)
30	98 (5)	.17 (.3)	.0069 (.002)	.0048 (.002)
31	99 (7)	88 (.86)	.0022 (.001)	.0006 (.001)
32	36 (2)	515.23 (41.4)	-.0044 (.002)	-.0033 (.002)
33	38 (1)	270.28 (25.4)	-.0059 (.004)	-.007 (.001)
34	38 (3)	83.64 (24.7)	-.0067 (.002)	-.0013 (.001)
35	39 (4)	7.23 (12.0)	-.0013 (.001)	-.0014 (.001)
36	39 (4)	5.33 (24.0)	.0004 (.001)	0 (.001)
37	42 (5)	14.82 (.3)	-.0099 (.001)	-.0027 (.001)
38	39 (4)	.18 (.5)	.0059 (.002)	.0017 (.002)
39	39 (4)	.12 (.3)	.0016 (.003)	.0063 (.003)
40	67 (3)	.20 (3.2)	.0021 (.002)	.0121 (.002)
41	64 (3)	2.94 (.7)	-.0002 (.001)	-.0002 (.001)
42	65 (3)	.54 (.4)	.0046 (.001)	.0011 (.001)
43	66 (3)	90.07 (35.2)	-.0044 (.002)	-.0050 (.002)
44	66 (4)	27.88 (5.6)	-.0066 (.001)	-.0016 (.00)

TABLE 3. Morphological classification summary

Slope	Drainage	Curvature downslope/across slope	Class
20 - 30	<1	*	1
20 - 30	>1	-/-	1
30 - 40	<1	0/0 to +/+	1
30 - 40	>1	-/- to 0/0	2
40 - 60	<6	-/- to +/+	3
40 - 60	>6	-/- to +/+	4
60 - 70	<1	-/- to +/+	4
60 - 70	>1	-/-	4
>70	*	*	4

* Variable not included.

FIGURE 9. Morphological hazard classification.

The morphological stability DEM-based map corresponds in the spatial distribution of the four stability classes to the multifactor slope stability map of the Norrish-Cascade watershed (Figure 2). The morphological DEM-based map, however, tends to overestimate terrain classified as moderate to high (classes 3 and 4) in comparison to the multifactor slope stability map. Similarly, terrain classified as low and moderately low (classes 1 and 2) has been underestimated by the DEM-based classification.

The discrepancy between these two maps is a product of the factors and variability of the hazard class criteria used to develop the two stability classifications, and of the spatial resolution of the original elevation data used in the DEM. The multifactor slope stability system relies on a greater number of factors in defining slope stability than does the DEM-based classification. The latter is based on combinations of slope angle, shape and slope position, whereas the former also includes material type and presence or absence of geomorphic processes. The class criteria for some factors, such as slope gradient, also varied between the two classification approaches. In general, the range of slope angles for each hazard class was lower for the morphological classification than for the multifactor approach.

The following example illustrates the differences. The morphological classification assigned a high hazard rating to all types of terrain with slopes greater than 31°. In contrast, the multifactor approach classified only a portion of terrain with slopes greater than 31° as a high slope stability hazard. It only included terrain consisting of till on slopes greater than 33° or colluvium on slopes greater than 36° undergoing modifications by gully processes, or escarpments in unconsolidated materials with slopes greater than 33°.

The spatial resolution of the elevation data used to create the morphological DEM-based stability map is insufficient to identify the steep sloping escarpments of unconsolidated materials as a high stability hazard. This type of terrain was classed as low to moderately low, as these escarpments are predominantly associated with fluvial or glaciofluvial landforms. The use of finer resolution elevation data should reduce this problem.

6.3 Clearcut Cluster Hazard Ratings

The individual DEM morphological clusters summarized in Table 2 were assigned a slope stability rating on the basis of the number of clearcut landslides per hectare (Table 4). The result of this classification is mapped in Figure 10.

In general, the classes generated by the clearcut cluster analysis coincide with the descriptions of the four classes of the multifactor approach presented by Howes (1987). For example, the slope and shape values of the DEM clusters generally agree with the multifactor slope and shape values of his multifactor classification. There are, however, some notable differences between the clearcut cluster and multifactor stability maps. The DEM clearcut cluster stability map has more area classed as moderate (class 3) and less area classified as moderately low (class 2) than does the multifactor stability map. The DEM cluster analysis also assigned a high rating (class 4) to a portion of the valley bottom rated as low by the multifactor scheme.

The difference between these maps is thought to be a result of the spatial resolution of the original elevation data used to generate the DEM. As in the case of the morphological classification, the failure to identify escarpments is the cause of some of the disagreement between the multifactor and DEM-based clearcut hazard classifications. Cluster 22 (Table 2), for example, should be classified as low but, because of a high number of slides associated with escarpments, it is classified as high.

The multifactor stability rating method used the presence of gully erosion processes as a factor in determining landscape units or groupings. Steep-sloped terrain undergoing these processes initiates frequent clearcut landslides (Howes 1987). Thus, the multifactor classification scheme assigned these areas a high stability rating (class 4) based on the density of landslides. The DEM-based clearcut stability map does not differentiate terrain subject to gully processes, because of the spatial resolution of the original elevation data. These areas were therefore grouped into the same class as those polygons that were not characterized by gullies.

Variation in the stability ratings between the multifactor and the DEM-based clearcut classifications may also be due to differences in the number of unique terrain cluster groups used in the multifactor classification. Many of the clusters generated had a limited amount of associated clearcut, so density statistics calculated for them may not be representative of the cluster as a whole. Some error in landslide densities for clusters may also result in the plotting of the landslide initiation sites.

TABLE 4. Clearcut classification summary

Cluster No.	No. of slides	Area clearcut (ha)	Density (slides/ha)	Class
1	0	13	0	0
2	19	103	.18	4
3	0	0	0	5
4	0	0	0	5
5	6	348	0	0
6	0	9	0	1
7	1	13	0	0
8	0	20	0	1
9	0	37	0	1
10	1	17	0	0
11	0	30	0	5
12	0	0	0	5
13	0	0	0	5
14	0	0	0	5
15	40	592	0	0
16	18	286	0	0
17	12	133	0	3
18	2	9	.22	4
19	0	4	0	1
20	0	4	0	1
21	2	32	0	3
22	34	138	.25	4
23	1	44	0	2
24	0	18	0	1
25	6	45	.13	4
26	0	23	0	1
27	3	14	.21	4
28	1	4	.25	4
29	0	0	0	5
30	0	0	0	5
31	2	5	.4	4
32	0	13	0	5
33	0	17	0	1
34	2	27	0	3
35	13	279	0	2
36	44	1070	0	2
37	1	4	.25	4
38	4	51	0	3
39	2	29	0	3
40	0	0	0	5
41	38	584	0	3
42	3	39	0	3
43	0	0	0	5
44	0	0	0	5

Class 1 = low, Class 2 = moderately low, Class 3 = moderate, Class 4 = high, Class 5 = unclassified

NORTHINGS AND EASTINGS IN METRES

HIGH

MODERATE

LOW

VERY LOW

UNCLASSIFIED

FIGURE 10. Clearcut hazard classification.

7 CONCLUSIONS

Our study shows that a rapid and objective evaluation of slope stability hazards can be obtained through the use of digital terrain models. The results obtained in this study are different from those obtained through the use of the more traditional multifactor approach. The reason is that the information content of the multifactor study is much greater, including data on bedrock geology and surficial materials, both of which contribute to the stability of slopes. Combined with published maps of bedrock geology and surficial material characteristics in a Geographical Information System, however, an approximation of the traditional multifactor map product is possible.

The slope stability methodology presented in this paper, although not directly comparable with the more traditional techniques of hazard evaluation, can significantly help in preliminary terrain evaluation projects. The intention of the demonstrated methodology is not to replace field and laboratory studies. The map products generated, however, will significantly reduce the time required to develop a preliminary evaluation.

A second conclusion of this study relates to the DEM used. Although the spatial resolution of the grid was 50 m, it was not sufficient to extract information on the gullying or the smaller escarpments in the larger stream channels. As Howes (1987) showed, these landforms are critical in the identification of areas' potential slope instability. Without this resolving power, the classifications obtained were correspondingly coarse. To resolve the smaller gullies, a DEM with a very fine resolution would be necessary. The costs of producing this model would be high, and the processing and storage requirements would also increase.

APPENDIX 1. FORTRAN Programme Listings

Enclosed are listings of the programmes used to generate the spatial derivatives and flow path model used in this study.

FORM.FOR

```
c
c               Routine to calculate the spatial derivatives using a third
c               order LaGrange polynomial (reference: Zevenbergen and Thorne 1987)
c
                Integer*4 nr,nc,ff,k,iii,ii,jj,l
                Real*4 Rz(3,700),out(700),a,b,c,d,e,f,g,h,i,si,sqg,sqh,temp
                Character Input*30,Output*30,ans*1,ans1*1
c
c               Input Criteria
c
                write (*,*)'Name of input file:'
                read(*,2) input
    2           format (A30)
                Write (*,*)'Name of output file:'
                Read(*,2) output
                Write(*,*) 'What is the size of a grid cell?'
                Read(*,*) SI
                Write (*,*) 'Does the file have a header record (Y/N):'
                Read (*,3) ans1

                Write(*,*)'Function (1-4)'
                Write(*,*)'1) Slope gradient'
                Write(*,*)'2) Slope aspect'
                Write(*,*)'3) Downslope curvature'
                Write(*,*)'4) Across slope curvature'
                Read(*,*) ff
c
c               Open the input and output data files
c
                Open (unit=7,file=input,status='old',form='formatted')
                Open (unit=8,file=output,status='unknown',form='formatted')
                if (ans1.eq.'y'.or.ans1.eq.'Y')then
                read(7,*) nr,nc
                else
                write(*,*) 'number of rows,columns:'
                read (*,*) nr,nc
                endif

                nrr=nr-2
                ncc=nc-2
                write(*,*) 'number of input rows, cols.:',nr,nc
                write(*,*) 'number of output rows, cols.:',nrr,ncc
                write (*,*) 'Is the output for Compugrd import?'
                read (*,3) ans
```

```
    3       format (a1)
            write (*,*)
            if (ans.eq.'n'.or.ans.eq.'N')then
            write (8,*) nrr,ncc
            endif
            k=1

c
c           Read matrix
c
            do 10 ii=1,3
            read (7,*) (rz(ii,jj),jj=1,nc)
   10       continue

c
c           Start main loop
c
            do 100 iii=1,nr-1

            write(*,1000) 'processing row #:',iii
 1000       format ('+',a20,i4)

c
c           Calculate the polynomial coefficients for 3 X 3 sub matrices
c
            do 300 l=1,nc-2
            d=(((rz(k+1,l)+rz(K+1,l+2))/2)-rz(K+1,l+1)) / (si*si)
            e=(((rz(k,l+1)+rz(k+2,l+1))/2)-rz(k+1,l+1)) / (si*si)
            f=(rz(k,l+2)+rz(k+2,l)-rz(k,l)-rz(k+2,l+2))/(4*(si*si))
            g=((-1*rz(k+1,l))+rz(k+1,l+2)) / (2*si)
            h=(rz(k,l+1)-rz(k+2,l+1)) / (2*si)

            qg=g**2
            sqh=h**2

c
c           Calculate the spatial derivatives
c
            if(ff.eq.1) out(l+1)=((sqg)+(sqh))**0.5
            if (ff.eq.2) then
            if((h.eq.0.and.g.eq.0).or.(g.eq.0))then
            out(l+1)=361
            else
            temp1=abs(h / g)
            temp=(atan(temp1))*57.958
            if(temp.lt.0)then
            out(l+1)=361
            else
            if(h.gt.0.and.g.gt.0)out(l+1)=270-(abs(temp))
            if(h.gt.0.and.g.lt.0)out(l+1)=90+(abs(temp))
            if(h.lt.0.and.g.lt.0)out(l+1)=90-(abs(temp))
            if(h.lt.0.and.g.gt.0)out(l+1)=270+(abs(temp))
```

```
                endif
                endif
                endif
                if (ff.eq.3)then
                if (g.eq.0.0.and.h.eq.0.0)then
                out(l+1)=0.00001
                else
                out(l+1)=(-2*((d*(sqg))+(e*(sqh))+(f*g*h)))
               :/((sqg)+(sqh))
                endif
                endif

                if (ff.eq.4)then
                if(g.eq.0.0.and.h.eq.0.0)then
                out(l+1)=0.00001
                else
                out(l+1)=(-2*((d*(sqh))+(e*(sqg))-(f*g*h)))
               :/((sqg)+(sqh))
                endif
                endif
      300       continue

c
c               Write raster to output file
c
                write(8,*) (out(l),l=2,nc-1)

                do 400 kk=2,3
                do 400 ll=1,nc
                rz(kk-1,ll)=rz(kk,ll)
      400       continue
                kk=3
                read(7,*,end=999) (rz(kk,ll),ll=1,nc)

      100       continue
      999       continue

c
c               Close files
c
                close (UNIT=7)
                close (UNIT=8)
                stop
                end
```

FLOW.FOR

```
c
c               Programme to calculate the area contributing to the flow
c               through a grid cell. The algorithm also considers the
c               slope of the grid cells and corrects the area conversion.
c               Note that the programme uses random (or direct) access files.
c               Written by K.O. Niemann, Department of Geography, U. of Victoria.
c

                real*4 in(3,700),out(700),out1(700),slope,elev(700)
                real*4 min,gs,temp,area,g,h,sqg,sqh,costemp,oldmin
                integer*4 i,j,ii,jj,kk,newi,newj,nrow,ncol,nrow1
                integer*4 hh,ix,row,col,mm,nn,outc(700),itemp
                character input*20,output*20,ans*1

c
c               Input parameters
c
     1001       write (*,'(" Name of input matrix: " \)')
                read (*,1) input

     1002       write (*,'(" Name of output matrix: " \)')
                read (*,1) output

c
c               The header information expected is the number of rows and columns in c your matrix
c

                write (*,*) 'Does your file have a header record? (y/n)'
                read (*,2) ans
     2          format (a1)

                if (ans.eq.'N'.or.ans.eq.'n')then

     1003       write (*,'(" Number of rows: " \)')
                read (*,*) nrow

     1004       write (*,'(" Number of columns: " \)')
                read (*,*) ncol
                else
                read (10,*) nr,nc
                endif

c
c               Open direct access files
c

                open(unit=10,file=input,status='old',form='formatted')
                open(unit=11,file=output,status='unknown',form='formatted')
                open(unit=12,status='scratch',access='direct',recl=ncol*4,
               : form='unformatted')
                open(unit=13,status='scratch',access='direct',recl=ncol*4,
               : form='unformatted')

     1005       write (*,'(" Size of gridcell: " \)')
                read (*,*) gs
     1          format (a20)
```

```
c
c               Initialize the output matrix correcting for the slope
c
                write(*,'(/" . . . Initializing Matrices"/)')
c
c               Note that the original dtm grid file does not need to be written
c               as a direct access file
c
                do 10 i=1,nrow
                read (10,*)(elev(j),j=1,ncol)
                do 11 j=1,ncol
                out(j)=0.0
      1         continue
                write (12,rec=i) (elev(j),j=1,ncol)
                write (13,rec=i)(out(j),j=1,ncol)
     10         continue
c
c               Echo to screen the number of rows
c
                write (*,*) 'Number of rows=',nrow
                temp=0.0
                area=0.0
                oldmin=999999.
c
c               Set first record to 2 and first column to 2
c
                j=2
                i=2
                row=2
                col=2
c
c               Read in three records from the input matrix
c
     99         continue
                if (i.eq.nrow)goto 999
                ix=0
                do 12 ii=row-1,row+1
                read(12,rec=ii) (elev(kk),kk=1,ncol)
                ix=ix+1
                do 121 hh=1,ncol
                in(ix,hh)=elev(hh)
    121         continue
     12         continue
c
c               Echo the location of the processing to the screen. This may be
c               deleted if you have a reasonably fast processor as the screen
c               will reduce the efficiency of the programme.
c
```

```
      write(*,1007) 'Processing Row:',i,'Col:',j,'Min:',min,'Newi:',
     :  newi,'Newj:',newj
1007  format ('+',a15,i3,a5,i3,a5,f5.0,a5,i4,a6,i4)

c
c     Find the minimum of 3 x 3 matrix
c
      min=999999.0
      ix=0

      do 20 ii=row-1,row+1
      ix=ix+1

      do 20 jj=col-1,col+1
      if (in(ix,jj).lt.min)then
      min=in(ix,jj)
      newi=ii
      newj=jj
      endif
20    continue

c
c     Check first to see if we are at the edge of the matrix
c

      if(newj.eq.ncol.or.newj.eq.1.or.newi.eq.nrow.or.newi
     :  .eq.1)goto 901

c
c     Calculate the slope between the new pixel and the surroundings.
c     This slope value will be used as correction factor for the area
c     of each pixel.
      c
      g=((-1*in(2,newj-1))+in(2,newj+1))/(2*gs)
      h=(in(1,newj)-in(3,newj))/(2*gs)
      sqg=g**2
      sqh=h**2
      slope=(sqg+sqh)**0.5

c
c     Get record which corresponds to the newi from output
c     matrix and write the new value to the out(newj) position.
c     Also correct for the slope position.
c

      read (13,rec=newi)(out(kk),kk=1,ncol)

      if (out(newj).eq.0.0)then
      costemp=cos(slope)
      area=(costemp*1)
      temp=(temp+area)
      out(newj)=out(newj)+temp
      else
      out(newj)=out(newj)+temp
      endif

      write (13,rec=newi)(out(kk),kk=1,ncol)
```

```
c
c               Set i to newi and j to newj and got back to reading in the
c               3 rows. first check to see if you are at edge of matrix
c
                if ((newi.eq.row.and.newj.eq.col).or.oldmin.eq.min)then
                j=j+1
                col=j
                row=i
                area=0.0
                temp=0.0
                if(col.ge.ncol.or.col.le.1)then
                j=2
                i=i+1
                col=j
                row=i
                temp=0.0
                area=0.0
                endif
                goto 925
                endif
                oldmin=min
      901       continue
                if(newj.eq.ncol.or.newj.eq.1.or.newi.eq.nrow.or.newi
               :  .eq.1.)then
                j=j+1
                if(j.eq.ncol)then
                j=2
                i=i+1
                endif
                col=j
                row=i
                temp=0.0
                area=0.0
                else
                row=newi
                col=newj
                endif
                if(i.eq.nrow)goto 999
      925       continue
                goto 99
      999       continue
c
c               Write the results to the output file
c
                do 9001 i=1,nrow
                read (13,rec=i) (out(j),j=1,ncol)
                write (11,*) (out(j),j=1,ncol)
```

```
 9001    continue
c
c
c       Close output files
c
        close (unit=10)
        close (unit=11)

        stop
        end
```

REFERENCES

Armstrong, J.E., D.R. Crandell, D.J. Easterbrook, and J.B. Nobel. 1965. Late Pleistocene stratigraphy and chronology in southwestern British Columbia and Northwestern Washington. Geolog. Soc. Am. 76: 321-330.

Burrough, P.A. 1986. Principles of Geographical Information Systems for Land Resources Assessment. Monographs on Soil and Resources Survey No. 12. Oxford Sci. Public. 193 p.

Carrara, A. 1983. Multivariate models for landslide hazard evaluation. Mathematical Geology 15:403-426.

Evans, I.S. 1972. General geomorphometry, derivatives of altitude and descriptive statistics. *In* Spatial analysis in geomorphology. Chorley, R.J. (editor) Methuen, London pp. 17-90.

Heerdegen, R.G. and M.A. Beran. 1982. Quantifying source areas through land surface curvature and shape. J. Hydrol. 57:359-373.

Howes, D.E. 1987. A terrain evaluation method for predicting terrain susceptible to post-logging landslide activity. B.C. Environ. Parks, Victoria, B.C. Tech Rep 28. 38 p.

Jensen, J.R. 1986. Introductory digital image processing: a remote sensing perspective. Prentice-Hall, Englewood Cliffs, N.J. 329 p.

O'Callaghan, J.F. and D.M. Mark. 1984. The extraction of drainage networks from digital elevation data. Computer Vision, Graphics and Image Processing 23:323-344.

Pack, R.T. 1985. Multivariate analysis of relative landslide susceptibility in Davis County, Utah. Ph.D. dissertation Utah State Univ., Ogden, Utah. 232 p.

Rib, H.T. and T. Liang. 1978 Recognition and identification. *In* Landslides: analysis and control. Schuster,R.J. and R.J.Krizek (editors) pp.34-80.

Roddick, J.A. 1965. Vancouver North, Coquitlam, and Pitt Lake map areas, British Columbia. Geol. Survey of Canada Memoir 335. 276 p.

Sarle, W.S. 1983. Cubic clustering criterion. SAS Tech. Rep. A-108. 49 p.

SAS. 1987. SAS/STAT guide for personal computers version 6 edition. SAS Institute Inc., Cary, N.C. 1028 p.

Sharpe, C.F. 1938. Landslides and related phenomena. Columbia Univ. Press., Columbia, S.C. 137 p.

Sidle, P.C. 1985. Relative importance of factors influencing landsliding in coastal Alaska. *In* Proc. 21st Annual Eng. Geology and Soils Eng. Symp. pp. 311-325.

Sidle, P.C., A.J. Pearce, and C.L. O'Loughlin. 1985. Hillslope stability and land use. Am. Geophys. Union. 141 p.

Swanston, D.N. 1974. Slope stability problems associated with timber harvesting in mountainous regions of the southwestern U.S. Dep. Agric. Forest Service, Gen. Tech. Rep. PNW-021. 22 p.

Varnes, D.J. 1978. Slope movement types and processes. *In* Landslides: analysis and control. R.L. Schuster and R.J. Krizek (editors) Special Report 176 National Academy of Science, National Res. Council, Washington, D.C., pp. 11-33.

Wolf, P.R. 1983. Elements of photogrammetry. McGraw-Hill, New York, N.Y. 628 p.

Yoeli, P. 1984. Cartographic contouring with computer and plotter. American cartographer 11:22-38.

Zevenbergen, L.W. and C.R. Thorne. 1987. Quantitative analysis of land surface topography. Earth surface processes and landforms 12:47-56.

Queen's Printer for British Columbia©
Victoria, 1992